

# Dipolariton formation in quantum dot molecules strongly coupled to optical resonators

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## Abstract.

In this theoretical work, we study a double quantum dot interacting strongly with a microcavity, while undergoing resonant tunneling. Effects of interdot tunneling on the light-matter hybridized states are determined, and tunability of their brightness degrees and associated dipole moments is demonstrated. These results predict dipolariton generation in artificial molecules coupled to optical resonators, and provide a promising scenario for control of emission efficiency and coherence times of exciton polaritons.

## INTRODUCTION

In recent years, interest for light generation from low dimensional structures coupled to electrodynamics cavities has increased noticeably [1, 2, 3]. In particular, quantum dots (QDs) have proved to be an excellent tool for experimental observation of purely quantum phenomena, like single photon emission and photon entanglement, both of which can be enhanced through an optical resonator by strengthening the coupling between the QD and the electromagnetic field [4, 5].

Microcavities confine light in a small volume and increase radiation-matter coupling as described by the Purcell effect [6, 7]. In such a strong coupling regime, the system eigenvectors are hybridized states of the QD and the cavity field. These kind of mixed states of light and matter are known as “exciton polaritons” (EP) [8]. Strong radiation-matter coupling for a QD inside a planar cavity has been successfully observed and progressively improved along this century [9, 10, 11].

On the other hand, coupling by resonant tunneling between adjacent QDs (artificial molecules) has been proposed as an efficient mechanism to improve tunability in zero dimensional systems [12, 13]. Between different alternatives to control tunneling in double quantum dot (DQD) structures, bias tuning has been found so far as the most successful [14, 15, 16].

In this work, we study the properties of EP modes for a DQD embedded in a microcavity, in such a way that interdot coupling and strong radiation matter interaction are simultaneously considered, and formation of polaritons with adjustable dipole moment (dipolaritons) and reduced brightness (dark polaritons), is explored.

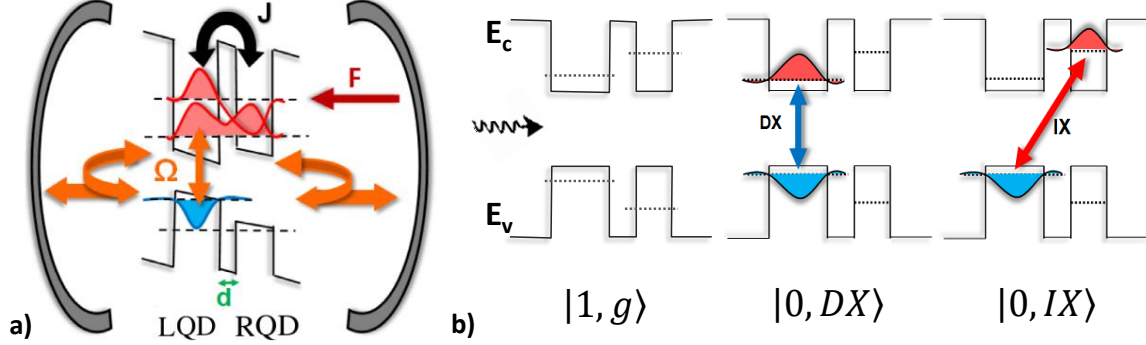
## MODEL

We consider an asymmetric double quantum dot with a slight difference on the intrinsic energy of the direct and indirect excitonic levels, coupled to a microcavity. Figure 1 a) depicts the proposed system, in which  $J$  represents the coupling between left and right dot (LD-RD), while figure 1 b) shows the configurations chosen for the basis of the subspace corresponding to the first rung of the Jaynes-Cummings (JC) ladder.

In absence of a bias field, the direct exciton (DX) coupled to a photonic mode would form a conventional polariton with a coupling energy given by the Rabi frequency  $\Omega$  (which in turn depends on the radiation-matter constant  $g$ ) [11]. On its side, the indirect exciton (IX) is assumed to be a dark state, given the reduced overlap between electron and hole.

Application of an external bias  $F$  on the DQD allows for tuning of the indirect exciton energy, and resonant tunneling between the  $|0, DX\rangle$  and  $|0, IX\rangle$  states can be achieved.

The tunneling rate  $J$  depends on the potential barrier experienced by the confined single particles, and is in principle unmodified by the cavity. For simplicity, hole tunneling can be reasonably neglected and then, only electron hopping is considered [16].



**FIGURE 1.** a) Schematics of the studied system b) Configuration basis

The Hamiltonian for the  $n$ -th JC rung in the above described basis reads ( $\hbar = 1$ )

$$\hat{H} = \omega_C \hat{n} - \Delta_{c,dx} \hat{\sigma}_{dx,g}^{\dagger} \hat{\sigma}_{g,dx}^{-} + (\Delta_{ix,dx} - \Delta_{c,dx} - e d F) \hat{\sigma}_{ix,g}^{\dagger} \hat{\sigma}_{g,ix}^{-} + g (\hat{a} \hat{\sigma}_{dx,g}^{\dagger} + \hat{a}^{\dagger} \hat{\sigma}_{g,dx}^{-}) - \frac{J}{2} (\hat{\sigma}_{dx,g}^{\dagger} \hat{\sigma}_{g,ix}^{-} + \hat{\sigma}_{ix,g}^{\dagger} \hat{\sigma}_{g,dx}^{-}), \quad (1)$$

where  $\omega_C$  is the cavity mode frequency,  $e$  is the electron charge,  $d$  is interdot distance (tunneling barrier width),  $\Delta_{ix,dx} = \omega_{IX} - \omega_{DX}$  ( $\Delta_{c,dx} = \omega_C - \omega_{DX}$ ) is the energy difference between the IX and DX (the cavity and the DX),  $\hat{n} = \hat{a}^{\dagger} \hat{a} + \hat{\sigma}_{dx,g}^{\dagger} \hat{\sigma}_{g,dx}^{-} + \hat{\sigma}_{ix,g}^{\dagger} \hat{\sigma}_{g,ix}^{-}$  is the polariton number operator (with  $\hat{a}$  and  $\hat{a}^{\dagger}$  the photon annihilation and creation operators, respectively), and  $\hat{\sigma}_{dx,g}^{\dagger} = |DX\rangle\langle g|$  ( $\hat{\sigma}_{ix,g}^{\dagger} = |IX\rangle\langle g|$ ) is the transition dipole operator between the DX (IX) and the DQD ground state.

## RESULTS

By diagonalizing the Hamiltonian in equation (1), the EP modes and their corresponding energies can be obtained. Figure 2 a) shows the uncoupled and EP energies for the first JC rung as functions of the bias field  $F$ . Meanwhile, figure 2 b) shows the fractional components of the basis states (Hopfield coefficients), for each of the EP modes.

The following realistic parameters were used in our calculations :  $\omega_C = 1320.7 \text{ meV}$ ,  $\Delta_{ix,dx} = 80 \text{ meV}$ ,  $\Delta_{c,dx} = 10.7 \text{ meV}$ ,  $d = 15 \text{ nm}$ ,  $J = 0.828 \text{ meV}$  and  $\Omega = J$ . Under such conditions, the tunneling resonance is found at  $-5.75 \text{ kV/cm}$ .

From the obtained coefficients shown in figure 2 b), two associated quantities can be computed to better elucidate the enriched polariton landscape produced by the presence of the second dot. Denoting the EP modes by  $|1, LP\rangle$ ,  $|1, MP\rangle$  and  $|1, UP\rangle$ ; and considering the superposition

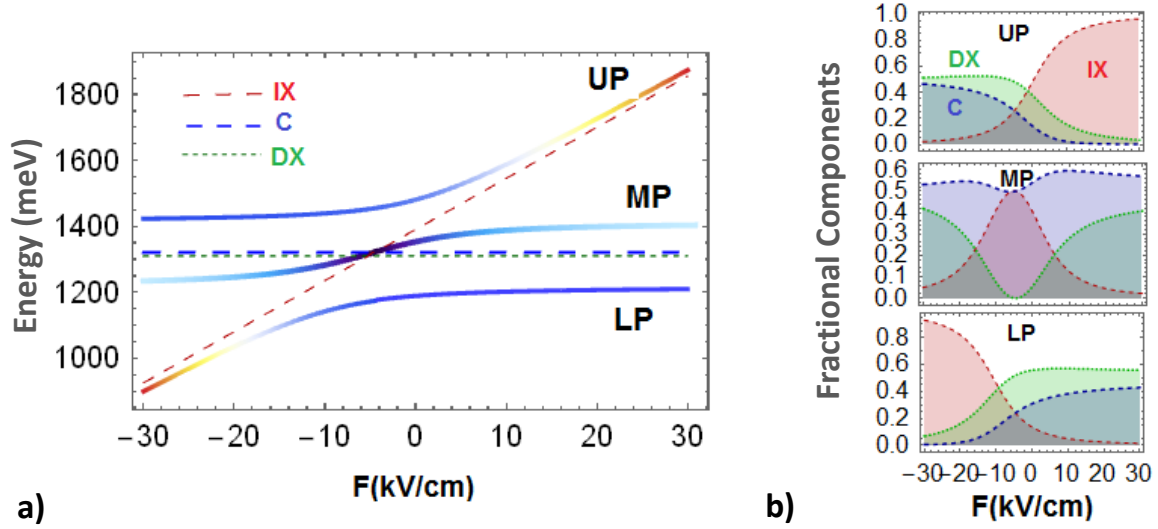
$$|1, \alpha\rangle = C_{1,g}^{\alpha} |1, g\rangle + C_{0,DX}^{\alpha} |0, DX\rangle + C_{0,IX}^{\alpha} |0, IX\rangle, \quad (2)$$

where  $\alpha = LP, MP, UP$ ; for each EP mode  $\alpha$ , we define the bright polariton degree

$$BPD = |C_{1,g}^{\alpha} C_{0,DX}^{\alpha}|, \quad (3)$$

and the exciton dipole moment

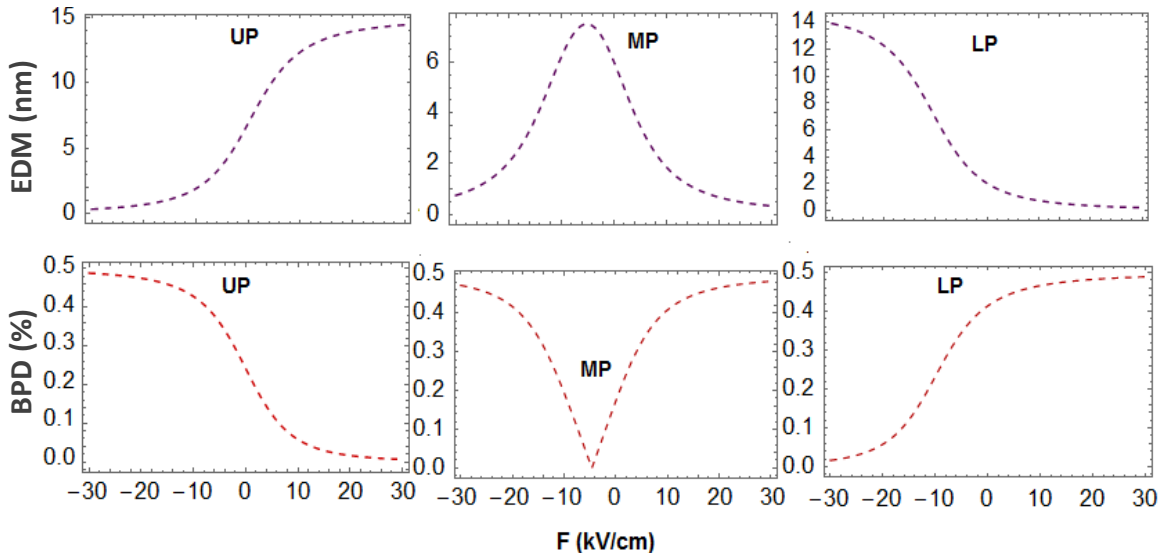
$$EDM = d |C_{0,IX}^{\alpha}|. \quad (4)$$



**FIGURE 2.** a) Lower, Middle and Upper polariton modes as functions of the bias field  $F$ . b) Fractional bare components for each of the polariton modes, as functions of  $F$ .

$BPD$  indicates how strong is the mixing between the DX and the cavity mode, and  $EDM$  accounts for the dipole moment associated to the corresponding EP mode.

Figure 3 shows the  $BPD$  and  $EDM$  as functions of the bias field  $F$ , for the same parameters as in figure 2. There, three regimes generated by the interplay between light-matter and interdot coupling, can be observed: (I) Conventional polariton [bright radiation-matter mixed states with negligible exciton dipole moment], for negative (positive) high values of  $F$  in the upper (lower) EP mode, and for positive and negative high values of  $F$  in the middle EP mode. (II) Dark dipolariton [mixed radiation matter states with negligible brightness and large dipole moment], for values of  $F$  just around the tunneling resonance, in the middle EP mode. (III) Bright dipolariton [mixed radiation matter states with significant brightness and exciton dipole moment], for moderate values of  $F$  (as long as they are not very close to the tunneling resonance), in the middle EP mode.



**FIGURE 3.** Bright polariton degree (top) and exciton dipole moment (bottom), for each EP mode, as functions of  $F$ .

Regimes (II) and (III) are particularly interesting. The former because this type of polariton states are expected to be long-living bosons, promising for exciton condensates and derived applications [17]. The later, because a tunable mixing between bright conventional polaritons and dark dipolaritons provides an optimal scenario for on demand switching between their respective main features.

## CONCLUSION

In summary, the polariton modes of a quantum dot molecule strongly coupled to a microcavity have been studied. By obtaining the dressed states and the corresponding fractional components of the double dot-cavity system in terms of a realistic tuning parameter, the possibility of generating polaritons with enhanced exciton dipole moment and adjustable emission efficiency was established.

These results suggest that the proposed combination of artificial molecule with optical resonator, could foster improved control of coherence times and emission of non-classical light from polaritons.

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